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Regional difference in runoff regimes and changes in the Yarlung Zangbo river basin

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Abstract

An improved understanding of runoff regimes and flow changes in the Yarlung Zangbo (YZ) river basin in the southern Tibetan Plateau (TP) is crucial for water resources management. However, regional characteristics in runoff regimes and changes are not comprehensively investigated in the YZ mostly due to the lack of hydrometeorological observations. Here, we comprehensively investigated runoff regimes and changes across six sub-basins in the YZ for 1971–2020 with a particular focus on the comparison between the upstream of the Nuxia (NX) basin and the downstream NX-Pasighat (NX-BXK), based on a newly generated precipitation dataset and a well-validated model with streamflow, glacier mass and snow cover observations. Our results reveal that large regional differences in runoff regimes and changes exist in the YZ basin. Firstly, runoff generation is dominated by rainfall in the entire YZ, and glacier runoff plays more important role in annual total runoff (19%) in the NX-BXK than other sub-basins. Secondly, annual runoff shows an increasing trend in the NX basin but a decreasing trend in the NX-BXK due to rain-induced runoff changes, resulting in a weak increasing trend (3.1 mm/10yr) in the YZ basin. Thirdly, total runoff increases of 5%–22% in the NX but decreases of 3%–20% in the NX-BXK in all seasons in 1998–2020 relative to the period 1971–1997. Finally, the NX basin faces a considerably hazard from extreme flood, but the NX-BXK basin faces more severe hydrological droughts. Glacier runoff shows limited roles in mitigating water shortages caused by drought in dry seasons, but it intensifies the flood frequency and severity among the basins in wet season. Our study offers a basic framework for clarifying the runoff

regimes and flow changes in the TP basins.

Keywords

Runoff Regimes, Runoff Changes, VIC-Glacier Hydrological Model, Yarlung Zangbo, Tibetan Plateau

Highlights

- A basic framework is provided to clarify runoff changes and the attribution in the TP basins.
- The NX-BXK makes the largest contribution (52%) to total runoff of the YZ basin.
- Annual runoff shows an increasing trend in the NX sub-basin but a decreasing trend in the NX-BXK, due to opposing precipitation changes.
- Glacier melt shows limited roles in mitigating water shortages caused by the drought, but it intensifies flood frequency and severity in the YZ.

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1 Introduction

The Yarlung Zangbo (YZ, Figure 1) River, also named the upper Brahmaputra, drains the southern Tibetan Plateau (TP) in China. As the largest river basin of the TP, the YZ basin and its two tributary (Lhasa and Nianchu river) basins serve as the main fresh water source of the Tibet autonomous region (TAR), and constitute the main agricultural region in the TAR (Yang et al., 1989; Zhong et al., 2014). Like elsewhere on TP, a rapid ongoing temperature rise (0.3–0.4°C) may influence runoff processes and water resources availability in the YZ basin (Yao et al., 2012; Li et al., 2018), and potentially increase the risk of natural hazards from floods or drought in the downstream region. Therefore, a comprehensive understanding of runoff regimes and flow changes in the YZ under the changing climate is crucial for decision making on water resources management.

The variability of hydrological processes is high within the YZ basin with an area of about 250,000 km^2 due to the differences in climate (e.g., Indian summer monsoon and local terrain effects) and physical characteristics (e.g., uneven distribution of glaciers and snow cover). Many studies of runoff regimes and changes were conducted using hydrological models in the YZ basin, but most simply focused on the region upstream of the Nuxia (NX) hydrological station (Figure 1) (Chen et al., 2017; Cuo et al., 2019; Su et al., 2016; Zhang et al., 2013; Zhao et al., 2019). Less attention was paid to the most glacierized downstream region between NX and Pasighat hydrological stations (NX-BXK, Figure 1), which accounts for about 65% of total glacier area in the YZ (Table 1). In addition, this region exhibits the largest glacier retreat in the TP, where length has decreased at a rate of 48.2m yr^{-1} and area was reduced at a rate of 0.57% yr^{-1} during the 1970s–2000s (Yang et al., 2013; Yao et al., 2012). Glacier melt can significantly modify streamflow regime, including the quantity, timing, and variability of flows over space and time (Barnett et al., 2005). In addition, ongoing atmospheric warming and water stress makes the TP vulnerable to drought, but glaciers are a uniquely drought-resilient source of water (Pritchard, 2019). Thus far, the very limited hydrological studies from the NX-BXK region show contradictory results due to the use of different hydrological models, forcing data and approaches. For example, Sun and Su (2020) suggested that total runoff was dominated by glacier melt in the NX-BXK, but Wang et al. (2021) suggested that total runoff was dominated by rain-induced runoff. Therefore, runoff regimes and changes and should be further investigated in the downstream region of the YZ.

Although many hydrological studies focus on the region upstream of the NX hydrological station, regional characteristics are still unclear in the basin. For example, runoff in the region between Yangcun and NX hydrological stations (YC-NX) contributes of 51% to total runoff at the NX hydrological station (Sun and Su, 2020); thus runoff regimes and changes in this sub-basin largely affect runoff changes in the entire NX basin. In addition, runoff changes in the Lhasa (LS) and Rikaze (RKZ) sub-basins, which are vital crop centers for the central Tibet Autonomous Region, are crucial to irrigation water resources. Therefore, it is important to

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investigate the runoff regimes and changes in different sub-basins of the NX, which will result in improved understanding of the underlying mechanisms of runoff changes.

Existing hydrological studies show large differences in runoff regimes and changes in the NX basin, which may due to variations in forcing inputs for hydrological model simulations. Accurate precipitation inputs are important for reliable hydrological model simulations (Su et al., 2008). However, high mountain precipitation in the YZ is still inadequately represented in either gauge-based precipitation, satellite-based precipitation, reanalysis-based estimates or outputs of regional climate models (Liu et al., 2020; Sun and Su, 2020; Sun et al., 2021). In addition, streamflow and glacier observations are inadequate for model calibration and validation, limiting simulation accuracy in the YZ basin. Most studies only validate hydrological models using streamflow observations, yet realistic runoff simulations at the catchment outlet cannot guarantee reasonable simulation results (Duethmann et al., 2014) because of the compensation between precipitation-induced runoff and glacier runoff. To address the above issues, in this study we collected precipitation observations at 280 gauges, streamflow observations at eight hydrological stations, glacier mass balance observations at two sites, and satellite-based glacier and snow cover area estimates in the YZ basin (Figure 1). These constitute a basin-wide observation dataset enabling us to validate hydrological models, and reveal runoff regimes and flow changes in the YZ basin.

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Based on the basin-wide observation dataset, in this study, runoff regimes, changes, and the attributions across six sub-basins in the YZ for 1971–2020 with a particular focus on the comparison between the NX and NX-BXK are comprehensively investigated using the Variable Infiltration Capacity (VIC)-Glacier hydrological model. Our intents are to: (1) use the model framework to identify runoff regimes and changes, and quantify the contributions of three major runoff components (glacier, rain-induced, and snowmelt runoff) to total runoff in the YZ and its subbasins; and (2) investigate responses of runoff and the three components to climate changes at annual, seasonal, and extreme flow scales. We expect these findings will provide a basic framework to study cryospheric basin hydrological cycles in the TP, and provide adopting strategies to water resource managers based on a solid scientific understanding. We introduce several novel components which may advance our understanding of the YZ hydrology:

(1) The analysis uncovers spatially varying runoff regimes and changes across six sub-basins of the YZ basin, associated with heterogeneous surface characteristics.

(2) A basin-wide observational hydrometeorology network is used to validate glacier-hydrological model to quantify runoff processes under climate-cryosphere changes.

(3) A comprehensive long-term precipitation dataset with a high spatiotemporal resolution (Sun et al., 2022) is used to improve hydrological simulations in this high-altitude basin.

2 Study Area

In this study, the entire YZ basin is divided into six sub-basins based on flow direction and

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locations of hydrological stations (Figure 1; Table 1). There are five sub-basins in the basin upstream of the Nuxia (NX) hydrological station, also named NX basin, and a sub-basin between Nuxia and Pasighat (NX-BXK) hydrological station. The NX basin includes the upstream sub-basins of Lhatse (LZ), Shigatse (RKZ) and Lhasa (LS) hydrological stations, the sub-basin between Lhatse and Yangcun (LZ-YC) hydrological station, and the sub-basin between Yangcun and Nuxia (YC-NX) hydrological station. The climate of the YZ is characterized by a wet and warm summer and a cool and dry winter, and precipitation is mostly dominated by summer monsoon (Figure S1 in Supporting Information). In addition, mean annual precipitation increases from upstream (283 mm) to downstream (1465 mm), with a mean of about 774 mm in the entire YZ basin (Table 1). All sub-basins show similiar seasonal patterns of temperature, with peaks mostly occurring in July–August (Figure S1). Glacier coverage ranges from 0.9% (LZ-YC) to 10.2% (NX-BXK), with an average of 3.3% in the entire YZ basin. The largest glacier coverage distributes in the YC-NX (2.8%) and NX-BXK (10.2%) sub-basins (Table 1). The snow cover fraction (SCF) ranges from 7% (RKZ) to 32% (NX-BXK), with an average of 19% in the YZ basin.

3 Data and Methodology

3.1 VIC-Glacier Hydrological Model

The physically based and distributed VIC hydrological model (Liang et al., 1994; Liang et al., 1996) linked with a simple degree-day glacier melt algorithm (Hock, 2003), referred to as VIC-

Glacier, is used in this study, which can simulate the physical exchange of water and energy among soil, vegetation, and atmosphere over a grid mesh. The VIC-Glacier model has a two layer energy-balance snow model (Cherkauer and Lettenmaier, 1999) and a frozen soil/permafrost algorithm (Cherkauer and Lettenmaier, 1999; 2003), and has been previously used in runoff simulations for several high-mountainous TP basins (Meng et al., 2019; Su et al., 2016; Sun and Su, 2020; Tong et al., 2016; Zhang et al., 2013; Zhao et al., 2019).

Here, the modeling framework at a 1/12°×1/12° (approximately 10 km ×10 km) spatial resolution and a three-hourly time step is adopted from Sun and Su (2020). The required forcing input data for the VIC-Glacier model include daily meteorological forcing data (precipitation, maximum and minimum temperatures, and wind speeds) with a spatial resolution of 10×10 km for 1961–2020, which is adopted from Sun et al. (2022). The daily gridded estimates from the newly released fifth-generation reanalysis (ERA5) precipitation of the European Centre for Medium-Range Weather Forecasts was corrected based on 580 rain gauges in the monsoon-dominated TP region and the machine learning algorithm (Sun et al., 2022). The developed precipitation data set was evaluated at a point scale by comparing it with gauge observations, and has been inversely assessed its potential utility in the VIC-Glacier hydrological simulation in the YZ basin (Sun et al., 2022).

According to the source of runoff generation, total runoff is partitioned into three components in this study: rain-induced runoff, snowmelt runoff, and glacier runoff. In this study, glacier runoff is defined as all water generated in the glacierized area, including rain-induced, snow melt, and ice melt in the glacierized area. The simulated total runoff from each grid cell can be calculated as

$$R_i = f \times R_{glac} + (1 - f) \times R_{vic} \quad (1)$$

where, R_i is the total runoff (mm) in grid I, f is the percentage of glacier area, and glacier area is updated every year, R_{glac} is the runoff (mm) from the glacier area, and R_{vic} is the runoff (mm) calculated from the VIC model (the sum of surface runoff and baseflow) in the non-glacierized area, including both rain-induced and seasonal snowmelt runoff.

The calculated glacier area and volume are updated every year in the model by the volume-area scaling approach (Bahr et al., 1997). We use an exponential form (equation 2), derived from the glacier observation in the western China (Liu et al., 2003), to convert the glacier area to volume for a basin:

$$V = 0.04S^{1.35} \quad (2)$$

where V is glacier volume and S is glacier area. The initial glacier volume is determined using glacier area from the first Glacier Inventory of China (CGI V1.0, http://westdc.westgis.ac.cn/glacier) dataset, and is updated every year with the snowfall accumulation and simulated ice melt from all the glacier cells. The updated glacier area is then validated by the Randolph Glacier Inventory (RGI V6.0) dataset.

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3.2 Model Calibration and Validation

Two categories of model parameters need to be calibrated for the VIC-Glacier model: (1) the degree day factor (DDF) related to glacier runoff simulation; and (2) the parameters of the VIC model related to runoff simulation in non-glacierized regions, mostly including the depth of the first and second soil layers (D1 and D2), the infiltration shape parameter (B_inf), and three base flow parameters (Ds, Ws, and Dsmax).

The VIC-Glacier hydrological model is calibrated by a systematic two-step approach. Observed streamflow, observed glacier mass balance, satellite-based glacier area and snow cover fraction estimates are applied to calibrate and validate the model in this study (see Table 2 for more details). The Nash-Sutcliffe efficiency (NSE), relative bias (RB, %), and correlation coefficient (CC), are applied to assess the performance of the hydrological model.

First, initial values of DDF parameters in the glacier model related to glacier and snowmelt are adopted from Sun and Su (2020). The glacier model is calibrated to match the glacier area observation from RGI V6 for 2000s–2010s, and validated by observed mass balance data from Gurenhekou and Parlung No.94 glacier sites (Table 2). Based on the good performance of glacier area simulation (with RB of mostly < 7%, Figure 2c), the final DDF are adjusted across six sub-basins (Table 1). In addition, the simulated variations in annual glacier mass balance are further validated with observations at Gurenhekou Glacier for 2005–2009 and Parlung

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No.94 Glacier for 2006–2018 in the YZ basin, which satisfactorily track the annual variations of the observed glacier mass balances, with CCs of 0.96 and 0.65, and RBs of -15% and -40% for the Gurenhekou (Figure 2a) and Parlung No.94 (Figure 2b) glaciers, respectively.

Second, the VIC-related model parameters (mostly B_inf and D2) are calibrated and validated with streamflow observations at eight hydrological stations across the six sub-basins. The VIC-Glacier model captures well the magnitudes and patterns of observed runoff at daily (Figure 3a), monthly (Figure S2) and seasonal (Figure 4) scales, with NSEs of 0.75 to 0.94 and RBs of -8% to 4.0% for the study basins. The closed agreements between the observed and simulated runoff are also seen at the annual scale (Figure 5), with a CC of 0.4–0.9. In order to further evaluate the model performance in simulating extreme streamflow, the flow duration curve (FDC) is used in the probability of daily runoff simulation, which represents the relationship between the magnitude and frequency of the daily streamflow in a particular river basin and provides an estimate of the percentage of time during the entire study period (Lutz et al., 2016). Here, the 95% and 5% probability of exceedance is defined as the threshold of flood and hydrological drought events. Simulated runoff can accurately capture the magnitudes of low and moderate daily observation but slightly underestimate flood prediction by less than 5% at the NX hydrological station (Figure 3b). After the careful calibration and validation, in this study, the final values of D1, D2 and B_inf for each grid cell are set to 0.1 m, 0.8–1.5 m, and 0.2 across six sub-basins, respectively.

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As additional validation of the model, the satellite-based SCF data are compared with the model simulations for 2001–2019 in the YZ basin (Figure 6). The simulated SCF follows the monthly variation of the satellite-based data with a CC of 0.60–0.82 ($p < 0.05$) and RB within ±12% among the basins, suggesting satisfactory performance of the VIC-Glacier model.

4 Results

4.1 Runoff Composition

Figure 7 shows mean monthly simulated rain-induced, snowmelt and glacier runoff, and mean annual contribution of them to total runoff across six sub-basins for 1971–2020. More than 60% of the annual total runoff occurs in June–September and 10%–15% in November–February in the YZ and all its sub-basins for 1971–2020 (Figure 7, Figure S1). The seasonal pattern of rain-induced runoff is consistent with that of total runoff. Due to co-occurrences of peak precipitation and temperature in June–September, the simulated glacier runoff mostly occurs during June–September for all the basins, with the peak in July and August. Snowmelt runoff in the YZ and its sub-basins occurs mostly during April–October, while the peak month of snowmelt differs among the sub-basins. Snowmelt runoff peaks in July–September in the LZ, RKZ, LS, and LZ-YC sub-basins (Figure 7a–d), which may be due to the melting of fresh snowfall in the warm season, thus helping to sustain the irrigation water supply. Snowmelt also shows a peak in the downstream sub-basins (Figure 7e, f), but the peak occurs in May–June. The seasonal pattern of snowmelt in the entire YZ basin is similar to that in downstream sub-

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basins, with the peak in May–June.

Large differences in runoff contribution to total runoff at Pasighat outlet exist across six sub-basins of the YZ basin (Figure 7). The NX-BXK contributes 52% to total runoff at the Pasighat outlet of the YZ basin (Figure 1), followed by YC-NX (25%), LS (10%), and other sub-basins, with contributions of 3%–6%. In addition, contributions of three runoff components to total runoff are also different across six sub-basins, mostly due to heterogeneous surface characteristics. Total runoff in the YZ and all its sub-basins is dominated by rain-induced runoff, which contributes 59%–72% to annual total runoff across six sub-basins, with an averaged contribution of 62% in the entire YZ basin. Snowmelt contributes 22% to annual total runoff in the YZ basin, and 14%–36% across six sub-basins, with the largest distributed in the LS sub-basin (36%). Glacier runoff contributes 16% to annual total runoff in the YZ basin, and 5%–19% to annual total runoff across six sub-basins. The largest contribution is in the NX-BXK (19%) and YC-NX (16%) sub-basins, where there is about 78% of the YZ total glacier area.

4.2 Runoff Changes and the Attribution

In this section, based on simulated total runoff and its three components, runoff changes and their attributions in the entire YZ and its sub-basins during 1971–2020 are investigated at annual, seasonal and extreme flow scales.

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4.2.1 Annual Scales

Figure 8 shows annual variations of the simulated total runoff and the three runoff components, and basin precipitation and temperature in the YZ basin during 1971–2020. Annual variations of precipitation, temperature, and simulated runoff in the sub-basins are presented in Figure S3–S7. Divergent annual runoff changes are evident among the sub-basins of the YZ. The simulated annual total runoff shows increasing trends of 8.1–18.8 mm/10yr for 1971–2020 in all sub-basins of the NX, except for the RKZ sub-basin (-1.1 mm/10yr), resulting in a significantly increasing trend of 9.4 mm/10yr ($p<0.05$) over the entire NX basin; this is mostly due to increases in rain-induced and glacier runoff, along with significant increases in precipitation and temperature (Figure 8a). In contrast, total runoff in the NX-BXK shows a significantly decreasing trend of 9.4 mm/10yr ($p<0.05$) for 1971–2020 (Figure 8b), resulting from a large decrease of rainfall-induced runoff (-22 mm/10yr) and seasonal snowmelt (-5.5 mm/10yr) from non-glacierized areas. It is worth noting that glacier runoff exhibits a significantly increasing trend (6.0 mm/10yr, $p<0.05$) in NX-BXK during 1971–2020, which partly compensated for the decreasing trend of total runoff in this sub-basin. As an integrated result of increased total runoff in the NX and decreased runoff in the NX-BXK, the total runoff in the entire YZ basin shows a weakly increasing trend of 3.1 mm/10yr, mostly due to increases of rain-induced and glacier runoff (Figure 8c). There is a strong correlation between annual variation of total runoff and rain-induced runoff in the YZ and all sub-basins (CC of 0.90–0.99, $p<0.05$), while total runoff shows only weak relationships with temperature and glacier runoff

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in the YZ and its sub-basins (Figure S8), suggesting a dominant role of rainfall-induced runoff from non-glacierized areas and minor impacts from glacier runoff on annual runoff.

Besides runoff changes, divergent annual variations of rain-induced, snowmelt and glacier runoff contributions for 1971–2020 are also apparent in the YZ basins (Table 3, Figure S9). The contribution of snowmelt to total runoff shows consistently decreasing trends among the basins, with significantly decreasing trends in the YZ basin (-1.1 %/10yr, $p<0.05$) and its NX sub-basin (-0.5 %/10yr, $p<0.05$). The contribution of glacier runoff decreases of -0.1 %/10yr in the NX sub-basin, while it increases in the NX-BXK sub-basin (0.8 %/10yr), mostly due to an increase in glacier runoff and a decrease of total runoff. In contrast, the contribution of rain-induced to total runoff increases in the NX sub-basin (1.1 %/10yr), while it decreases in the NX-BXK sub-basin (-0.7 %/10yr), resulting in an increasing trend of 0.2 %/10yr in the entire YZ basin.

Cuo et al. (2019) examined the precipitation and streamflow mutations by the Mann-Kendall analysis in the YZ basin, and suggested that precipitation shows no mutation while streamflow mutates in 1997 at NX hydrological station. Based on long-term runoff observation, this abrupt change is also displayed in this study. Trends in total runoff are opposite before and after the year 1998 in the YZ and its NX and NX-BXK sub-basins, due to opposing trends in precipitation (Table 3). Annual total runoff shows increasing trends (8.9–48.1 mm/10yr) in the basins during 1971–1997, mostly due to an increasing trend of rain-induced runoff, seasonal snowmelt and glacier runoff. However, total runoff shows insignificantly decreasing trends (-0.3 to -3.3 mm/10yr) during 1998–2020. It may be attributed to a decreasing trend of rain-induced by the weakening Indian monsoon after the period 1998–2000 (Liu et al., 2012; Wu and Duan, 2008; Wu and Duan, 2009; Yang et al., 2014a). It is worth noting that, the decreasing trend of precipitation is faster in NX-BXK (-16.0 mm/10yr) than that in NX (-7.0 mm/10yr, Table 3). This difference may result from the different influences of the weakening Indian monsoon during 1998–2000 (Figure S10). The NX-BXK basin is more sensitive than NX to the weakening Indian monsoon during 1998–2000 (Figure S10). However, the decreasing trend of total runoff is slower in NX-BXK (-0.3 mm/10yr) than that in NX (-3.3 mm/10yr, Table 3) during 1998–2000, resulting from different influences of glacier runoff on total runoff between NX and NX-BXK sub-basins. A faster increasing trend of glacier runoff in NX-BXK (16 mm/10yr), than that in NX (0.7 mm/10yr, Table 3), partly compensates for the faster decreasing trend of rain-induced runoff, resulting in a slower decreasing trend of total runoff in NX-BXK. Therefore, glacier runoff has been playing an increasing role in runoff changes as a result of accelerated warming in the region.

4.2.2 Seasonal Scales

Changes in melt water from glaciers and seasonal snow modify total runoff regimes with respect to both quantity and timing, and thus are of particular importance to water availability in warm and dry seasons (Barnett et al., 2005). Relative to the period 1971–1997, divergent seasonal changes in total runoff are apparent in the YZ basin during 1998–2020. For the NX basin, total runoff tends to increase by about 5%–22% in all seasons, with the largest increases appearing during May–August (11%–22%), mostly due to increases in rain-induced and glacier runoff. The smallest increases are during December–February (4.8%–5.7%), mostly due to increases in rain-induced runoff in the NX (Figure 9a, d; Table S1). Snowmelt runoff strongly increases during March–May (24%–50%) due to early snow melting (Figure 9d; Table S1), which may be beneficial to agricultural water supplies. On the contrary, total runoff decreases by about 3%–20% in all seasons in the NX-BXK sub-basin (Figure 9b; Table S1) due to decreases in rain-induced runoff and seasonal snowmelt. This indicates a trend towards drier conditions, although increased glacier runoff compensates slightly for the loss of total runoff in July–August (Figure 9e). As an integrated result of seasonal changes of runoff in NX and NX-BXK, total runoff in YZ increases by 3.0%–20.0% in June–September, mostly due to increases in rain-induced and glacier runoff, while it decreases in the other months because of decreased rain-induced runoff and seasonal snowmelt (Figure 9c, f).

The distinct seasonal changes of rain-induced, snowmelt, and glacier runoff largely determine the seasonal changes of their contributions to total runoff in the entire YZ basin and its NX and NX-BXK sub-basins. Relative to 1971–1997, the rain-induced contribution increases by 5%–8% during May–October in the NX for 1998–2020, but the glacier and snowmelt contribution decreases by -0.3% to -2% and -5% to -7% in these months, respectively (Figure 9g, Table S1).

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On the contrary, the contributions of rain-induced runoff and snowmelt decrease by -2% to -6% during May–October in the NX-BXK, but glacier contribution increases by 2%–7% in these months (Figure 9h, Table S1), showing increased importance of this season in sustaining summer water supplies in the NX-BXK. As an integrated result, for the entire YZ basin (Figure 9i) glacier contribution increases by 0.5%–2% (Table S1) during June–October, and the seasonal changes of rain-induced and snowmelt contributions to total runoff are similar to that in the NX basin.

4.2.3 Extreme Flow Scales

The magnitude and timing of flow extremes tend to be altered under climate change. Contrasting extreme frequency between hydrological drought and flood days for 1971–2020 exist in the YZ and its sub-basins (Figure 10). Flood frequency shows a decreasing trend of -1 days/10yr for 1971–2020, but drought frequency shows an increasing trend of 3 days/10yr in the YZ basin (Figure 10c, Table S2), which could lead to the droughts of higher duration and severity. This contrast also exist in the NX and NX-BXK sub-basins (Figure 10a,b; Table S2). In addition, opposing trends occur between these two sub-basins, whether drought or flood events. Drought days shows a decreasing trend of -6 days/10yr in the NX, but an increasing trend of 6 days/10yr in the BXK (Figure 10a,b; Table S2), mostly due to opposing trends in precipitation (Figure 8). On the contrary, flood days shows an increasing trend of 6 days/10yr in the NX, but a decreasing trend of -3 days/10yr in the BXK (Figure 10a,b; Table S2). This is

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similiar to the tendency of annual maximum daily runoff (Figure 10d–f). The annual-maximum daily runoff increases in the NX, but decreases in the NX-BXK. Trends in annual-maximum daily runoff are also opposite before and after the year 1998 in the YZ and its NX and NX-BXK sub-basins, with increasing trends (0.1–0.7 mm/10yr) during 1971–1997 and decreasing trends of -0.1 to -0.5 mm/10yr during 1998–2020 (Figure 10d–f, Table S2).

As with the runoff changes described above, extreme frequency changes are mostly influenced by monsoon precipitation in the YZ basin. It is worth noting that glacier runoff plays an increasing role during 1971–2020 in both annual and summer water supplies in the YZ (Figure 7–9), and it is a uniquely drought-resilient source of water in the high-mountainous regions (Pritchard, 2019). Flow duration curves for simulated daily total runoff, glacier runoff, and precipitation-induced runoff (rain-induced and snowmelt) during 1971–2020 in the YZ and its NX and NX-BXK basins are shown in Figure 10, and we also compare mean annual contribution of glacier runoff to total runoff between the drought years and all years for 1971–2020, suggesing that mean annual glacier contribution is greater in the drought years than all year. For example, glacier runoff contributes 29% to mean annual total runoff in the drought years in the NX-BXK, which is higher than its contribution (19%) for the period 1971–2020. It suggests that glacier runoff typically make a useful contribution to water supplies in study basin where summers are dry; however, glacier runoff shows limited roles in protecting water shortages from the drought in dry seasons in the YZ basin (Figure 10g–i), mostly due to the

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limited glacier contribution compared to the water volume generated by rainfall in the monsoon-dominated basins.

Glacier melt intensifies the flood frequency and severity among the basins in wet season (Figure 10 g–i). The flow duration curves (FDCs) for precipitation-induced runoff are lower than those from total runoff, especially in the flood events (exceedance probability of > 95%), implying increases in both the magnitude and frequency of maximum daily flow. In particular, in the time series of runoff solely induced by precipitation (rainfall and snowmelt), peak flows higher than 2–8 mm/day typically have an exceedance frequency of 95%, while this exceedance frequency is strongly reduced to 85%–90% in the time series of total runoff that is additionally fed by glacier meltwater. In addtion, the magnitudes of flood events in total runoff are higher in the NX-BXK (exceedance probability of > 86%) than the NX basin (exceedance probability of > 90%), due to larger contribution of glacier runoff to total runoff in the NX-BXK sub-basin.

5 Discussion

5.1 Runoff Changes in the Downstream Sub-basin

The NX-BXK sub-basin, with the largest glacier area and runoff contribution to total runoff of the YZ basin, is more sensitive to climate and cryosphere changes than the other sub-basins. Therefore, runoff changes in this basin raise considerable concern for downstream life-supporting water supplies.

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Between existing research and our study, results are contradictory on runoff changes in the NX-BXK. Wang et al. (2021) suggested that total runoff showed an increasing trend of 6.4×10^8 m^3/yr during 1998–2019. However, in our study, simulated total runoff exhibited a decreasing trend of about -0.3 mm/10yr (-7.5×10^8 m^3/yr) during 1998–2020 in the sub-basin (Figure 8, Table 3). This difference between the two studies is mostly because of the trends in precipitation estimates used for the hydrological model (Figure 11). Precipitation shows increasing trends of 90 mm/10yr during 1981–2016 and 19 mm/10yr during 1998–2016 in Wang et al. (2021), compared with decreasing trends of -110.0 mm/10yr during 1981–2016 and -84.0 mm/10yr during 1998–2016 in this study. In addition, a decreasing trend of atmospheric moisture during the monsoon season in the sub-basin also partly confirms the rationality of the reconstructed precipitation used in this study as model input.

The varition of precipitation datasets for high mountains may result in large differences in meltwater contribution (Sun and Su, 2020). Less attention about the contribution of glacier runoff in the YZ basin was paid to the NX-BXK (Table 4), and large inconsistencies in glacier contributions also existed in these studies (Table 4), mostly resulting from uncertainties in forcing inputs and parameters for VIC-Glacier models. For example, Sun and Su (2020) suggested that mean annual glacier runoff contributed of about 45% to total runoff in the NX-BXK sub-basin for 1980–2000 using a hydrological model without calibration and validition due to a lack of runoff observation in the sub-basin. Based on newly collected rain gauge data, and runoff, glacier mass balance, and glacier and snow cover observations in the NX-BXK, glacier runoff is simulated by the well-validated VIC-Glacier model forced by a comprehensively reconstructed long-term precipitation dataset in this study. The contribution of glacier runoff to total runoff is updated to 19% during 1971–2020 in the NX-BXK sub-basin.

Reliable parameters are crucial for accurate runoff simulation by hydrological models. The DDF is the most sensitive parameter for degree-day glacier model (Hock, 2003). Zhang et al. (2013) studied the sensitivity of glacier melt runoff to the parameters of DDFs, suggesting that average annual glacier runoff would decrease/increase about 10% with the decrease/increase of each one unit (mm $°C^{-1}$ day^{-1}) in DDF. In this work, the DDF parameters used in this study are derived based on observed glacier mass balance data, but intensively validations on glacier melt (e.g. observed glacier mass balance and satellite-based glacier area estimates). In addition, monthly runoff observation from eight hydrological stations are collected to further validate parameters, ensuring that the model set-up is suitable for our modelling purposes.

5.2 Implications for Water Management

Comprehensive understanding of regional runoff characteristics and changes shows important implications for water management in the river basin. First, runoff regimes and changes are different among the sub-basins of the YZ; thus, our findings of regional runoff changes among

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sub-basins of the YZ basin are important to make informed policy decisions on local water management. For instance, for the LS and NX basin, increased flows occur in April–September related to increased rainfall and snowmelt peak to earlier spring, which may thus alleviate a shortage of irrigation water in the drought-prone early stages of the growing season (Immerzeel et al., 2010). On the contrary, for the NX-BXK basin, decreased flows are mostly occurred in September–May related to decreased rainfall and snowmelt, which may be paid attention by hydrological government to considerable effects on water security, stress, and availability. In addition, climate changes have resulted in an increase of nature hazards largely associated with cryosphere in recent years, such as glacier lake outburst floods and glacier collapses. On 16 and 29 October 2018, a glacier collapse blocked main course of the river and generated a dam-breaching flood in the downstream sub-basin of the YZ, which threatened the living security of more than 20,000 people in the Mainling County and Medog County (Chen et al., 2020; An et al., 2021; Zhao et al., 2022). Therefore, effects of glacier change on hydrological processes need to be further investigated, and early warning of nature hazards associated with cryosphere is suggested to be placed emphasis in the NX-BXK, which accounts for about 65% of total glacier area and about 52% of runoff in the YZ (Table 1).

Second, the YZ basin are threatened by hazard from both extreme floods and hydrological drought (Figure 10). Therefore, our findings will be benefit to make informed policy decisions on protecting downstream populations from the worst effects of the flood and drought events.

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The Yarlung-Brahmaputra basin is one of the world's largest and most populated region, providing life-supporting services to about 70 million people from the China, India, Banglasesh and Bhutan countries (Pradhan et al., 2021). Higher flood risks in wet season and drought risks in dry season will be particularly relevant for human safety and agricultural production in both the upper and downstream basins of the YZ (Liu et al., 2018; Gao et al., 2019). Especially for downstream region, vast agriculture areas along the main rivers and in the delta's floodplain will likely experience higher flood water levels from upper regions, thus having higher risks of reduced productivity and crop failure (Hoang et al., 2016). Therefore, some mitigation and adaptation strategies are urgently needed to solve water security problems from flood or drought hazard in this basin. Our study offers a basic framework for clarifying the extreme flood and drought events, and investigating the roles of glacier runoff in extreme events in the monsoon-dominated basin of the TP.

6 Conclusions

In this study, runoff regimes, flow changes and the attribution are comprehensively investigated across six sub-basins in the YZ for 1971–2020 with a particular focus on the comparison between the NX and NX-BXK based on a newly generated precipitation dataset and the well-validated large-scale VIC-Glacier model with observed streamflow at eight hydrological stations, glacier mass balance data at two sites, and satellite-based glacier and snow cover estimates. Large regional differences in runoff regimes and flow changes in the YZ basin were

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observed. The main features of these differences are summarized below.

1. Regional differences in runoff regimes are presented in the YZ basin. The NX-BXK contributes 52% to total runoff at the Pasighat outlet of the YZ basin, followed by the YC-NX (25%), LS (10%), and other sub-basins (3%–6%). Although runoff generation in the entire YZ is dominated by rain-induced (59%–72%), glacier runoff plays more important roles in annual total runoff in the downstream sub-basins (16%–19%) than other sub-basins, especially in summer (23%–35%).

2. Regional differences in annual runoff changes are found in the YZ basin. Annual runoff generally increases during 1971–2020 in all sub-basins of the NX basin (8–19 mm/10yr), except for the RKZ sub-basin. The NX-BXK sub-basin (-9.4 mm/10yr, $p<0.05$) shows a significant decrease, which results in a weak increasing trend of 3.1 mm/10yr in the entire YZ basin. Total runoff trends reverse after 1998 for all the sub-basins of the YZ, with increasing trends during 1971–1997 and decreasing trends during 1998–2020. However, the decreasing trend of total runoff is slower in the NX-BXK (-0.3 mm/10yr) than the NX (-3.3 mm/10yr) due to the stronger increases of glacier runoff (16.1 mm/10yr) in the NX-BXK. Annual runoff changes in the YZ and its six sub-basins are dominated by precipitation-induced runoff from non-glacierized areas, with only minor impacts from glacier runoff.

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3. Regional differences in seasonal runoff changes are apparent in the YZ basin. Relative to 1971–1997, mean monthly total runoff increased by 5%–22% in NX for 1998–2020, mostly due to increases in rain-induced and glacier runoff, while monthly runoff decreased by 3%–20% in NX-BXK because of decreases in precipitation-induced runoff. As an integrated result of seasonal runoff changes in these basins, total runoff in the YZ basin increased by 3%–20% during June–September, primarily due to increases in rain-induced and glacier runoff, while total runoff decreased in the other months because of decreased precipitation-induced runoff.

4. Regional differences in extreme frequency of flood and drought are apparent in the YZ basin. The NX basin faces a considerably hazard from extreme flood, with an increasing trend of 6 days/10yr. However, more severe hydrological droughts are likely to exacer-bate ongoing water stress in the NX-BXK sub-basin.

5. Regional differences in the importance of glacier runoff to water supplies are apparent in the YZ basin. Glacier runoff plays an increasing role in both annual and seasonal water supplies during 1971–2020 in the entire YZ as well as in its NX-BXK sub-basin. This is evidenced by increased glacier runoff and its contribution to total runoff. Glacier runoff shows limited roles in mitigating water shortages caused by the drought in dry seasons in the YZ basin, but it intensifies flood frequency and severity among the basins in wet season.

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Acknowledgments

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Code and data availability

The first Chinese Spatial Glacier Inventory is available from http://westdc.westgis.ac.cn/glacier. The Randolph Glacier Inventory 6.0 is available from http://www.glims.org/RGI/. The snow cover area data of the MODIS 10CM are available from https://nsidc.org/data. Observed runoff data are from the Tibetan Hydrological Bureaus. Observed glacier mass balance data at Gurenhekou and Parlung No.94 are collected from the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (http://www.tpdc.ac.cn). All codes used to produce the results are available upon request to the authors.

Author Contributions

He Sun: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Visualization, Funding acquisition, Writing draft. Tandong Yao: Conceptualization, Resources, Visualization, Funding acquisition, Writing (review and editing). Fengge Su: Writing (review and editing). Wei Yang: Editing and providing glacier mass balance data. Guifeng Huang:

Methodology, Resources. Deliang Chen: Writing (review and editing).

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

An, B., Wang, W., Yang, W., Wu, G., Guo, Y., Zhu, H., Gao, Y., Bai, L., Zhang, F., Zeng, C., Wang, L., Zhou, J., Li, X., Li, J., Zhao, Z., Chen, Y., Liu, J., Li, J., Wang, Z., Chen, W., and Yao, T.: Process, mechanisms, and early warning of glacier collapse-induced river blocking disasters in the Yarlung Tsangpo Grand Canyon, southeastern Tibetan Plateau, Sci Total Environ, 151652, https://doi.org/10.1016/j.scitotenv.2021.151652, 2021.

Bahr, D. B., Meier, M. F., and Peckham, S. D.: The physical basis of glacier volume - area scaling, J. Geophys. Res. Solid Earth, 102, 20355-20362, https://doi.org/10.1029/97jb01696, 1997.

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 303-309, https://doi.org/10.1038/nature04141, 2005.

Chen, C., Zhang, L., Xiao, T., and He, J.: Barrier lake bursting and flood routing in the Yarlung Tsangpo Grand Canyon in October 2018, J. Hydrol., 583, https://doi.org/10.1016/j.jhydrol.2020.124603, 2020.

https://doi.org/10.5194/hess-2023-16
Preprint. Discussion started: 8 February 2023

Chen, X., Long, D., Hong, Y., Zeng, C., and Yan, D.: Improved modeling of snow and glacier melting by a progressive two-stage calibration strategy with GRACE and multisource data: How snow and glacier meltwater contributes to the runoff of the Upper Brahmaputra River basin?, Water Resour. Res., 53, 2431–2466, https://doi.org/10.1002/2016WR019656, 2017.

Cuo, L. and Zhang, Y.: Spatial patterns of wet season precipitation vertical gradients on the Tibetan Plateau and the surroundings, Sci. Rep., 7, 5057, https://doi.org/10.1038/s41598-017-05345-6, 2017.

Cuo, L., Li, N., Liu, Z., Ding, J., Liang, L., Zhang, Y., and Gong, T.: Warming and human activities induced changes in the Yarlung Tsangpo basin of the Tibetan plateau and their influences on streamflow, J. Hydrol-Reg. Stud., 25, https://doi.org/10.1016/j.ejrh.2019.100625, 2019.

Duethmann, D., Peters, J., Blume, T., Vorogushyn, S., and Güntner, A.: The value of satellite-derived snow cover images for calibrating a hydrological model in snow-dominated catchments in Central Asia, Water Resour. Res., 50, 2002-2021, https://doi.org/10.1002/2013wr014382, 2014.

Gao, C., Liu, L., Ma, D., He, K., and Xu, Y. P.: Assessing responses of hydrological processes to climate change over the southeastern Tibetan Plateau based on resampling of future climate scenarios, Sci Total Environ, 664, 737-752, https://doi.org/10.1016/j.scitotenv.2019.02.013, 2019.

Hoang, L. P., Lauri, H., Kummu, M., Koponen, J., van Vliet, M. T. H., Supit, I., Leemans, R.,

https://doi.org/10.5194/hess-2023-16
Preprint. Discussion started: 8 February 2023

Hydrology and Earth System Sciences
Open Access
Discussions

Kabat, P., and Ludwig, F.: Mekong River flow and hydrological extremes under climate change, Hydrol. Earth Syst. Sci., 20, 3027-3041, 10.5194/hess-20-3027-2016, 2016.

Hock, R.: Temperature index melt modelling in mountain areas, J. Hydrol., 282, 104-115, https://doi.org/10.1016/s0022-1694(03)00257-9, 2003.

Kan, B., Su, F., Xu, B., Xie, Y., Li, J., and Zhang, H.: Generation of High Mountain Precipitation and Temperature Data for a Quantitative Assessment of Flow Regime in the Upper Yarkant Basin in the Karakoram, J. Geophys. Res. Atmos., 123, 8462-8486, https://doi.org/10.1029/2017jd028055, 2018.

Li, C., Su, F., Yang, D., Tong, K., Meng, F., and Kan, B.: Spatiotemporal variation of snow cover over the Tibetan Plateau based on MODIS snow product, 2001-2014, Int. J. Climatol., 38, 708-728, https://doi.org/10.1002/joc.5204, 2018.

Liang, X., Lettenmaier, D. P., and Wood, E. F.: One-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model, J. Geophys. Res. Atmos., 101, 21403-21422, https://doi.org/10.1029/96jd01448, 1996.

Liang, X., Lettenmaie, D. P., Wood, E. F., and Burges, S. J.: A simple hydrologically based model of land-surface water and energy fluxes, J. Geophysical Research, 99:, 14415–14428, https://doi.org/10.1029/94jd00483, 1994.

Liu, L., Pan, S. L., Bai, Z. X., and Xu, Y. P.: Potential application of hydrological ensemble prediction in forecasting flood and its components over the Yarlung Zangbo River Basin, China,

https://doi.org/10.5194/hess-2023-16
Preprint. Discussion started: 8 February 2023

Hydrology and Earth System Sciences
Discussions

Hydrol. Earth Syst. Sci. Discuss., 1-33, https://doi.org/10.5194/hess-2018-179, 2018.

Liu, L., Gu, H., Xie, J., and Xu, Y. P.: How well do the ERA‐Interim, ERA‐5, GLDAS‐2.1 and NCEP‐R2 reanalysis datasets represent daily air temperature over the Tibetan Plateau?, Int. J. Climatol., https://doi.org/10.1002/joc.6867, 2020.

Liu, S., Sun, W., Shen, Y., and Li, G.: Glacier changes since the Little Ice Age maximum in the western Qilian Shan, northwest China, and consequences of glacier runoff for water supply, J. Glaciol., 49, 117-124, https://doi.org/10.3189/172756503781830926, 2003.

Liu, Y., Wu, G., Hong, J., Dong, B., Duan, A., Bao, Q., and Zhou, L.: Revisiting Asian monsoon formation and change associated with Tibetan Plateau forcing: II. Change, Clim. Dynam., 39, 1183-1195, https://doi.org/10.1007/s00382-012-1335-y, 2012.

Lutz, A. F., Immerzeel, W. W., Kraaijenbrink, P. D., Shrestha, A. B., and Bierkens, M. F.: Climate Change Impacts on the Upper Indus Hydrology: Sources, Shifts and Extremes, PLoS One, 11, e0165630, https://doi.org/10.1371/journal.pone.0165630, 2016.

Meng, F. C., Su, F. G., Li, Y., and Tong, K.: Changes in Terrestrial Water Storage During 2003-2014 and Possible Causes in Tibetan Plateau, J. Geophys. Res. Atmos., 124, 2909-2931, https://doi.org/10.1029/2018jd029552, 2019.

Miao, L., Li, S., Zhang, F., Chen, T., Shan, Y., and Zhang, Y.: Future Drought in the Dry Lands of Asia Under the 1.5 and 2.0 °C Warming Scenarios, Earth's Future, 8, https://doi.org/10.1029/2019ef001337, 2020.

Niu, Q., Liu, L., Heng, J., Li, H., and Xu, Z.: A Multi-Index Evaluation of Drought

Characteristics in the Yarlung Zangbo River Basin of Tibetan Plateau, Southwest China, Front. Earth Sc., 8, https://doi.org/10.3389/feart.2020.00213, 2020.

Pradhan, N. S., Das, P. J., Gupta, N., and Shrestha, A. B.: Sustainable Management Options for Healthy Rivers in South Asia: The Case of Brahmaputra, Sustainability, 13, https://doi.org/10.3390/su13031087, 2021.

Pritchard, H. D.: Asia's shrinking glaciers protect large populations from drought stress, Nature, 569, 649-654, https://doi.org/10.1038/s41586-019-1240-1, 2019.

Su, F., Hong, Y., and Lettenmaier, D. P.: Evaluation of TRMM Multisatellite Precipitation Analysis (TMPA) and Its Utility in Hydrologic Prediction in the La Plata Basin, J. Hydrometeorol., 9, 622-640, https://doi.org/10.1175/2007jhm944.1, 2008.

Su, F., Zhang, L., Ou, T., Chen, D., Yao, T., Tong, K., and Qi, Y.: Hydrological response to future climate changes for the major upstream river basins in the Tibetan Plateau, Glob. Planet. Change, 136, 82-95, https://doi.org/10.1016/j.gloplacha.2015.10.012, 2016.

Su, F., Pritchard, H. D., Yao, T., Huang, J., Ou, T., Meng, F., Sun, H., Li, Y., Xu, B., Zhu, M., and Chen, D.: Contrasting Fate of Western Third Pole's Water Resources Under 21st Century Climate Change, Earth's Future, 10, https://doi.org/10.1029/2022ef002776, 2022.

Sun, H. and Su, F.: Precipitation correction and reconstruction for streamflow simulation based on 262 rain gauges in the upper Brahmaputra of southern Tibetan Plateau, J. Hydrol., 590, https://doi.org/10.1016/j.jhydrol.2020.125484, 2020.

Sun, H., Su, F., He, Z., Ou, T., Chen, D., Li, Z., and Li, Y.: Hydrological evaluation of high-

https://doi.org/10.5194/hess-2023-16
Preprint. Discussion started: 8 February 2023

resolution precipitation estimates from the WRF model in the Third Pole river basins, J. Hydrometeorol., https://doi.org/10.1175/jhm-d-20-0272.1, 2021.

Sun, H., Yao, T., Su, F., He, Z., Tang, G., Li, N., Zheng, B., Huang, J., Meng, F., and Ou, T. J. J. o. H.: Corrected ERA5 precipitation by machine learning significantly improved flow simulations for the Third Pole basins, J. Hydrometeorol., 23, https://doi.org/10.1175/JHM-D-22-0015.1, 2022.

Tong, K., Su, F., and Xu, B.: Quantifying the contribution of glacier meltwater in the expansion of the largest lake in Tibet, J. Geophys. Res. Atmos., 121, 11158-11173, https://doi.org/10.1002/2016jd025424, 2016.

Wang, A., Wang, Y., Su, B., Kundzewicz, Z. W., Tao, H., Wen, S., Qin, J., Gong, Y., and Jiang, T.: Comparison of Changing Population Exposure to Droughts in River Basins of the Tarim and the Indus, Earth's Future, 8, https://doi.org/10.1029/2019ef001448, 2020.

Wang, Y., Wang, L., Zhou, J., Yao, T., Yang, W., Zhong, X., Liu, R., Hu, Z., Luo, L., Ye, Q., Chen, N., and Ding, H.: Vanishing glaciers at southeast Tibetan Plateau have not offset the declining runoff at Yarlung Zangbo, Geophys. Res. Lett., https://doi.org/10.1029/2021gl094651, 2021.

Wu, G. and Duan, A.: Weakening Trend in the Atmospheric Heat Source over the Tibetan Plateau during Recent Decades. Part I: Observations, J. Clim., 21, 3149-3164, https://doi.org/10.1175/2007jcli1912.1, 2008.

Wu, G. and Duan, A.: Weakening Trend in the Atmospheric Heat Source over the Tibetan

https://doi.org/10.5194/hess-2023-16
Preprint. Discussion started: 8 February 2023

Hydrology and Earth System Sciences
Open Access
Discussions

Plateau during Recent Decades. Part II: Connection with Climate Warming, J. Clim., 22, 4197-4212, https://doi.org/10.1175/2009jcli2699.1, 2009.

Yang, W., Yao, T., Guo, X., Zhu, M., Li, S., and Kattel, D. B.: Mass balance of a maritime glacier on the southeast Tibetan Plateau and its climatic sensitivity, J. Geophys. Res. Atmos., 118, 9579-9594, https://doi.org/10.1002/jgrd.50760, 2013.

Yang, W., Guo, X., Yao, T., Yang, K., Zhao, L., Li, S., and Zhu, M.: Summertime surface energy budget and ablation modeling in the ablation zone of a maritime Tibetan glacier, J. Geophys. Res. Atmos., 116, https://doi.org/10.1029/2010jd015183, 2011.

Yang, Y., Gao, D., and Li, B.: Study on the moisture passage on the lower reaches of the Yarlung Zangbo river, Sci. China (Series B) 32, 580-593, 1989.

Yang, Z., Zhuo, M., Lu, H., Ma, P., and Zhou, K.: Characteristics of precipitation variation and its effects on runoff in the Yarlung Zangbo River basin during 1961–2010, Journal of Glaciology and Geocryology, 36, 166-172 (in chinese), 2014b.

Yao, T.: Recent glacial retreat in High Asia in China and its impact on water resource in Northwest China, Sci. China (Series D), 47, 1065, https://doi.org/10.1360/03yd0256, 2004.

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D. B., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nat. Clim. Chang., 2, 663-667, https://doi.org/10.1038/nclimate1580, 2012.

Zhang, L., Su, F., Yang, D., Hao, Z., and Tong, K.: Discharge regime and simulation for the

https://doi.org/10.5194/hess-2023-16
Preprint. Discussion started: 8 February 2023

upstream of major rivers over Tibetan Plateau, J. Geophys. Res. Atmos., 118, 8500-8518, https://doi.org/10.1002/jgrd.50665, 2013.

Zhao, C., Yang, W., Westoby, M., An, B., Wu, G., Wang, W., Wang, Z., Wang, Y., and Dunning, S.: Brief communication: An approximately 50 Mm³ ice-rock avalanche on 22 March 2021 in the Sedongpu valley, southeastern Tibetan Plateau, The Cryosphere, 16, 1333-1340, https://doi.org/10.5194/tc-16-1333-2022, 2022.

Zhao, Q., Ding, Y., Wang, J., Gao, H., Zhang, S., Zhao, C., Xu, J., Han, H., and Shangguan, D.: Projecting climate change impacts on hydrological processes on the Tibetan Plateau with model calibration against the Glacier Inventory Data and observed streamflow, J. Hydrol., 573, 60-81, https://doi.org/10.1016/j.jhydrol.2019.03.043, 2019.

Zhong, L., Ma, Y., Fu, Y., Pan, X., Hu, W., Su, Z., Salama, M. S., and Feng, L.: Assessment of soil water deficit for the middle reaches of Yarlung-Zangbo River from optical and passive microwave images, Remote Sens. Environ., 142, 1-8, https://doi.org/10.1016/j.rse.2013.11.008, 2014.

https://doi.org/10.5194/hess-2023-16
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Captions:

Figure 1. Location and topography of the Yarlung Zangbo (YZ) river basin. Numbers 1 to 6 show the sub-basins of Lhatse (LZ), Lhatse-Yangcun (LZ-YC), Shigatse (RKZ), Lhasa (LS), Yangcun-Nuxia (YC-NX), and Nuxia-Pasighat (NX-BXK), respectively.

Figure 2. Annual time series of observed and simulated glacier mass balance at (a) Gurenhekou for 2005–2009 and (b) Parlung No.94 for 2006–2018, and (c) mean annual glacier coverage (%) during 2000–2010 from the VIC-Glacier model simulation and satellite-based observation over the entire YZ basin and its sub-basins.

Figure 3. (a) Time series and (b) flow duration curve of observed and simulated daily runoff at Nuxia hydrological station for 1971–1980.

Figure 4. Mean monthly observed and simulated runoff at eight hydrological stations of sub-basins in the YZ for 1971–2015 (1981–2000 for YG and 2004–2013 for BM). Abbreviations LZ, RKZ, LS, LZ-YC, YC-NX, NX, YG and BM represent the upstream basins of Lhatse, Shigatse, Lhasa, the regions between Lhatse and Yangcun, between Yangcun and Nuxia, Nuxia, Yigong and Bomi, respectively.

Figure 5. Annual time series of observed and simulated runoff at nine hydrological stations in sub-basins of the YZ for 1971–2015 (1981–2000 for YG, 2004–2013 for BM and 2015–2019 for MT). Abbreviations LZ, RKZ, LS, LZ-YC, YC-NX, NX, YG, BM and MT represent the upstream basins of Lhatse, Shigatse, Lhasa, the regions between Lhatse and Yangcun, between Yangcun and Nuxia, Nuxia, Yigong, Bomi and Motuo, respectively. The asterisk indicates 95% significance confidence level.

Figure 6. Monthly time series of snow cover fraction (%) from the VIC-Glacier model simulation and satellite-based observations over the entire YZ basin and its four sub-basins for 2001–2019. The asterisk indicates 95% significance confidence level.

Figure 7. Mean monthly simulated rainfall, snowmelt, and glacier runoff, and their contribution to total annual runoff in the YZ and its sub-basins for 1971–2020.

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Figure 8. Annual variations of precipitation, temperature, total runoff and three runoff components (rainfall, glacier and snowmelt runoff) in the YZ and its sub-basins for 1971–2020, respectively. Linear trends are indicated by dashed lines, and corresponding values are also indicated. Asterisks indicate the 95% significance level

Figure 9. Changes in (a–c) mean monthly total runoff, (d–f) three components, and (g–i) their contributions to total runoff for the period 1998–2020 relative to the period 1971–1997 in the entire YZ basin and its NX and NX-BXK sub-basins.

Figure 10. (a–c) Extreme flood and drought days, (d–f) annual maximum daily runoff, and (g–i) flow duration curves for simulated daily runoff during 1971–2020 in the YZ and its NX and NX-BXK basins.

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Table 1. Characteristics of the six sub-basins in the Yarlung Zangbo River.

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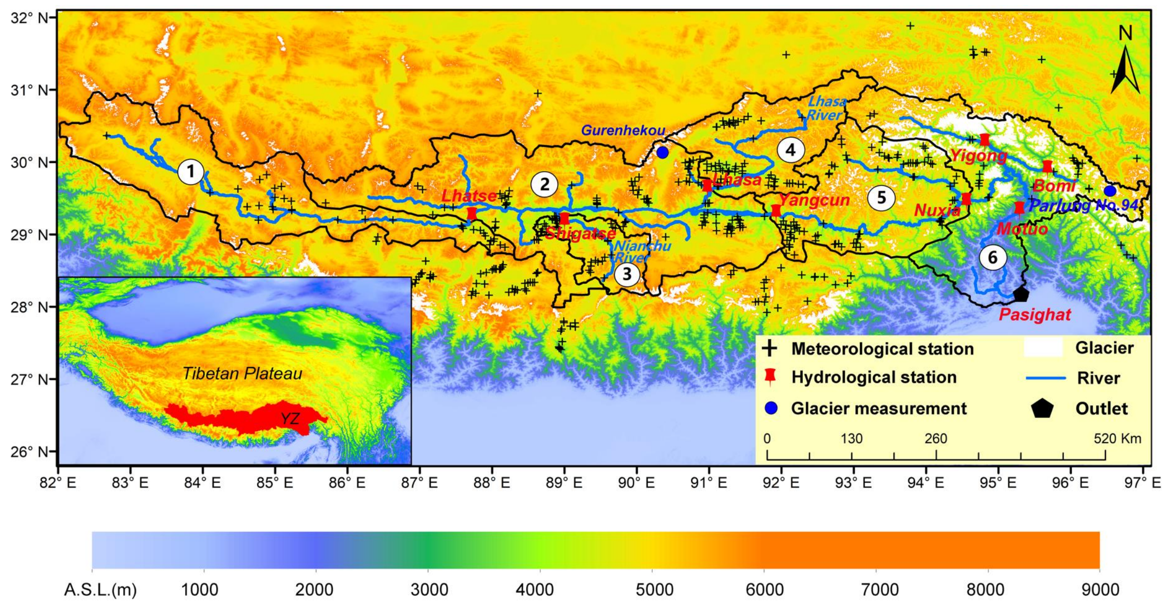

Figure 1. Location and topography of the Yarlung Zangbo (YZ) river basin. Numbers 1 to 6 show the sub-basins of Lhatse (LZ), Lhatse-Yangcun (LZ-YC), Shigatse (RKZ), Lhasa (LS), Yangcun-Nuxia (YC-NX), and Nuxia-Pasighat (NX-BXK), respectively.

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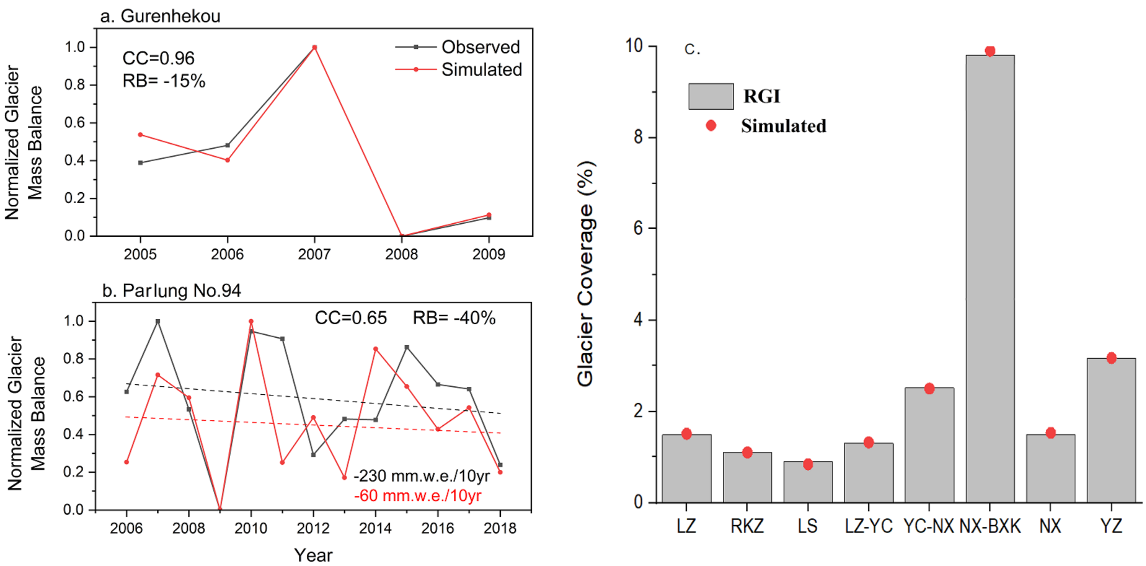

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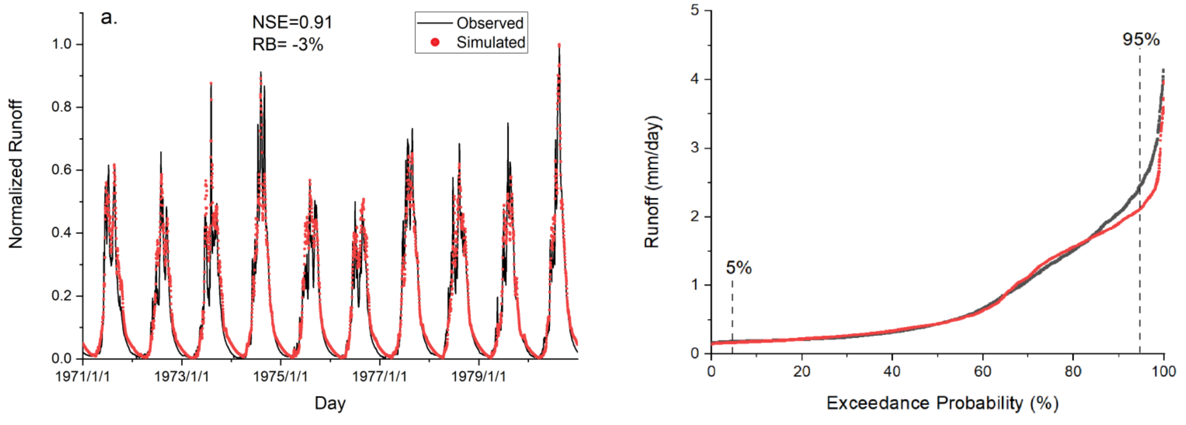

Figure 3. (a) Time series and (b) flow duration curve of observed and simulated daily runoff at Nuxia hydrological station for 1971–1980.

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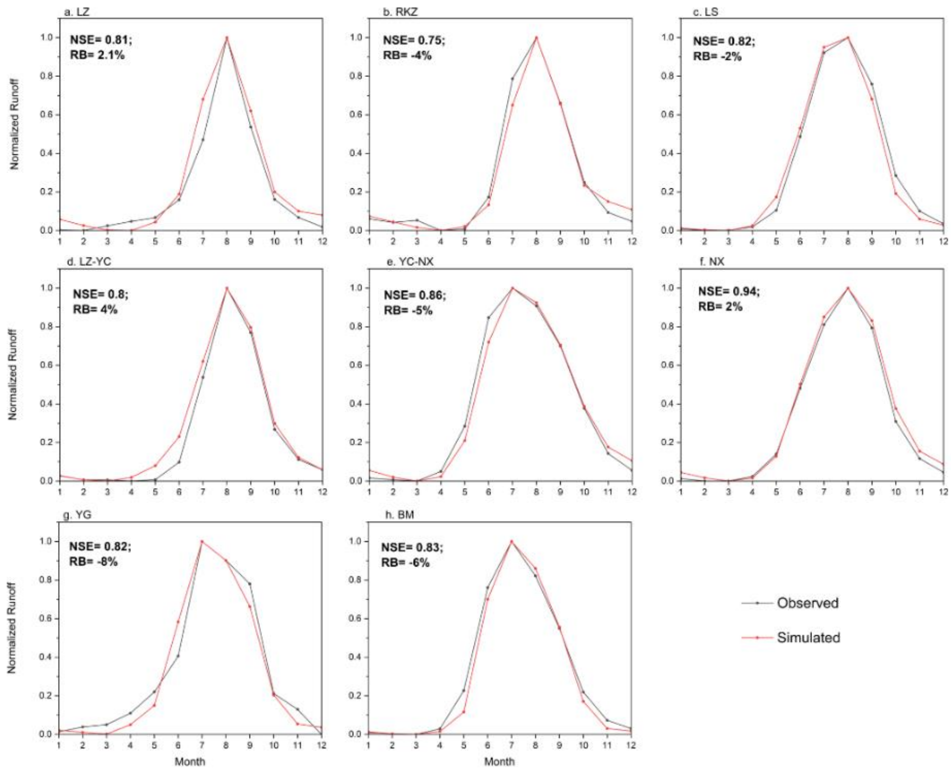

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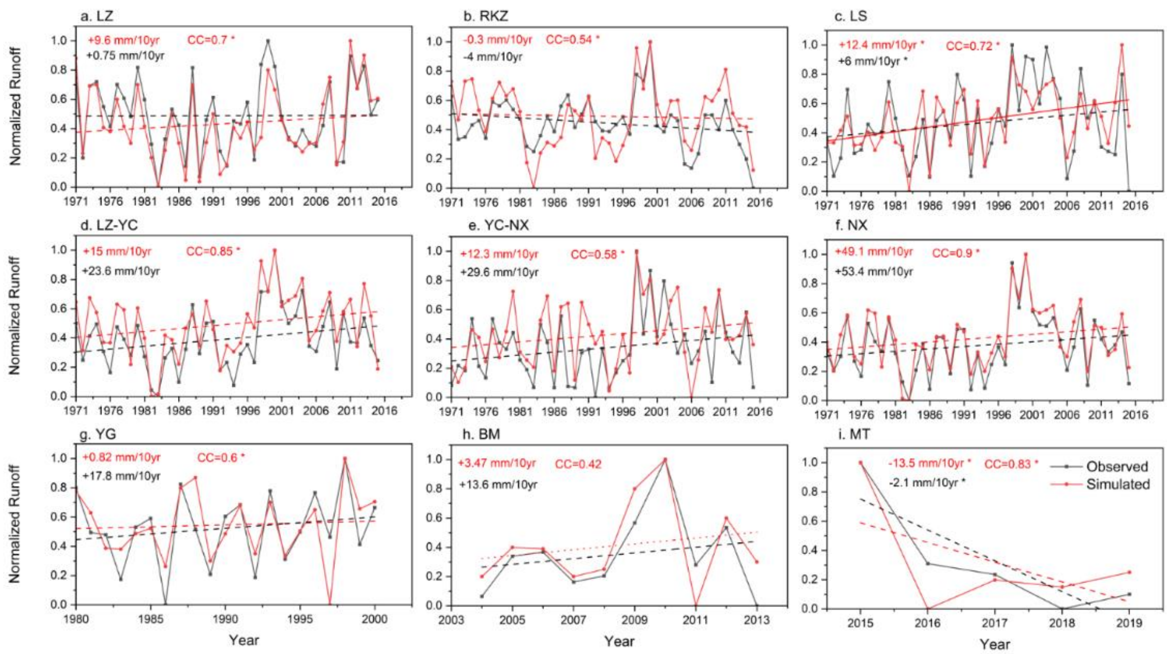

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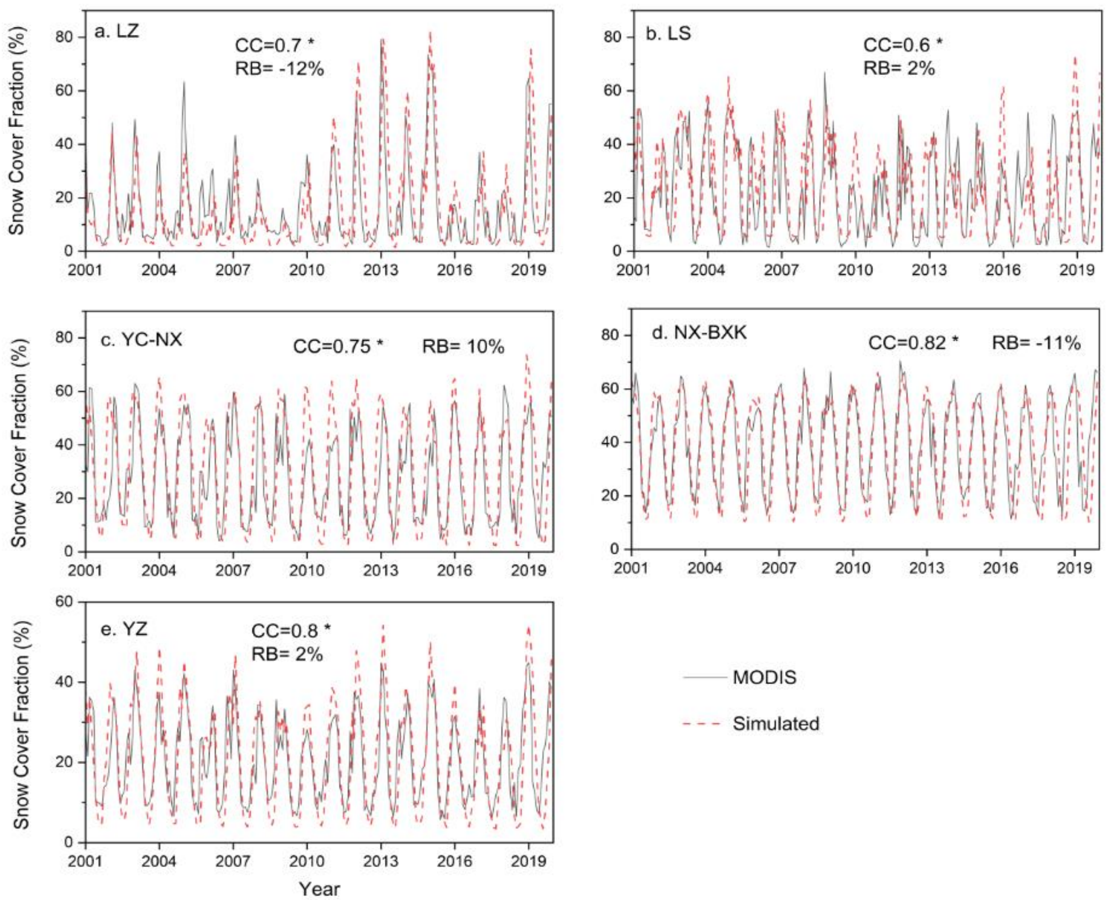

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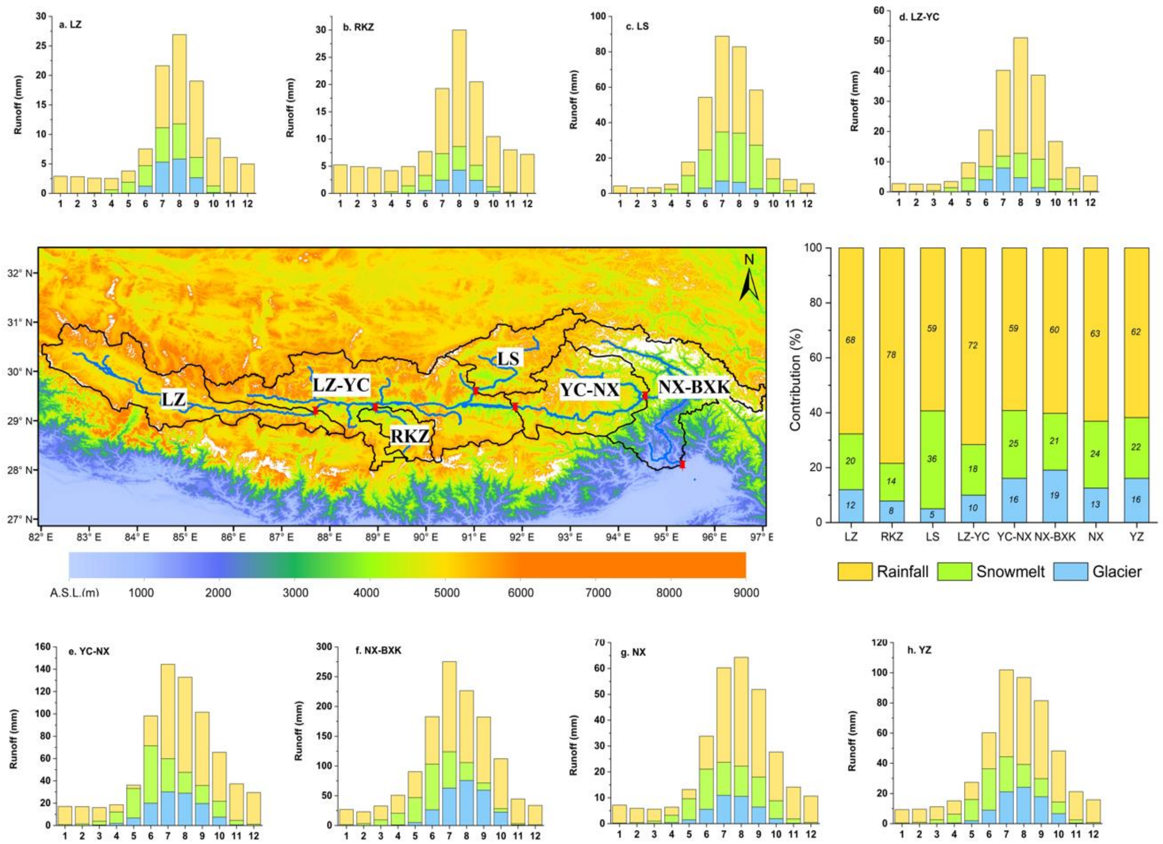

Figure 7. Mean monthly simulated rainfall, snowmelt, and glacier runoff, and their contribution to total annual runoff in the YZ and its sub-basins for 1971–2020.

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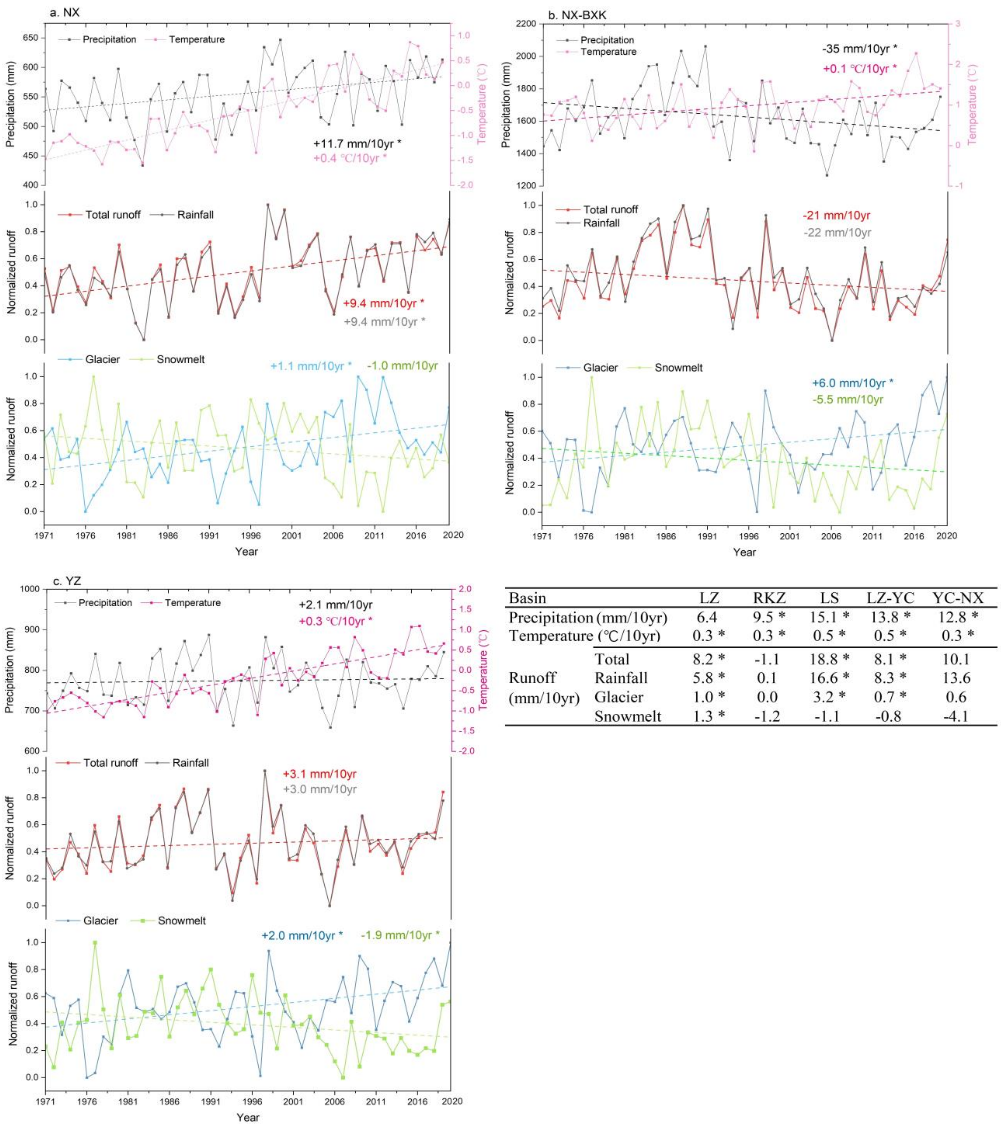

Basin		LZ	RKZ	LS	LZ-YC	YC-NX
Precipitation (mm/10yr)		6.4	9.5 *	15.1 *	13.8 *	12.8 *
Temperature (℃/10yr)		0.3 *	0.3 *	0.5 *	0.5 *	0.3 *
Runoff (mm/10yr)	Total	8.2 *	-1.1	18.8 *	8.1 *	10.1
	Rainfall	5.8 *	0.1	16.6 *	8.3 *	13.6
	Glacier	1.0 *	0.0	3.2 *	0.7 *	0.6
	Snowmelt	1.3 *	-1.2	-1.1	-0.8	-4.1

Figure 8. Annual variations of precipitation, temperature, total runoff, and three runoff components (rainfall, glacier, and snowmelt runoff) in the YZ and its sub-basins for 1971–2020, respectively. Linear trends are indicated by dashed lines, and corresponding values are also indicated. Tendency results for sub-basins are shown in the inset table. The number of each figure are calculated with actual magnitudes. Asterisks indicate the 95% significance level.

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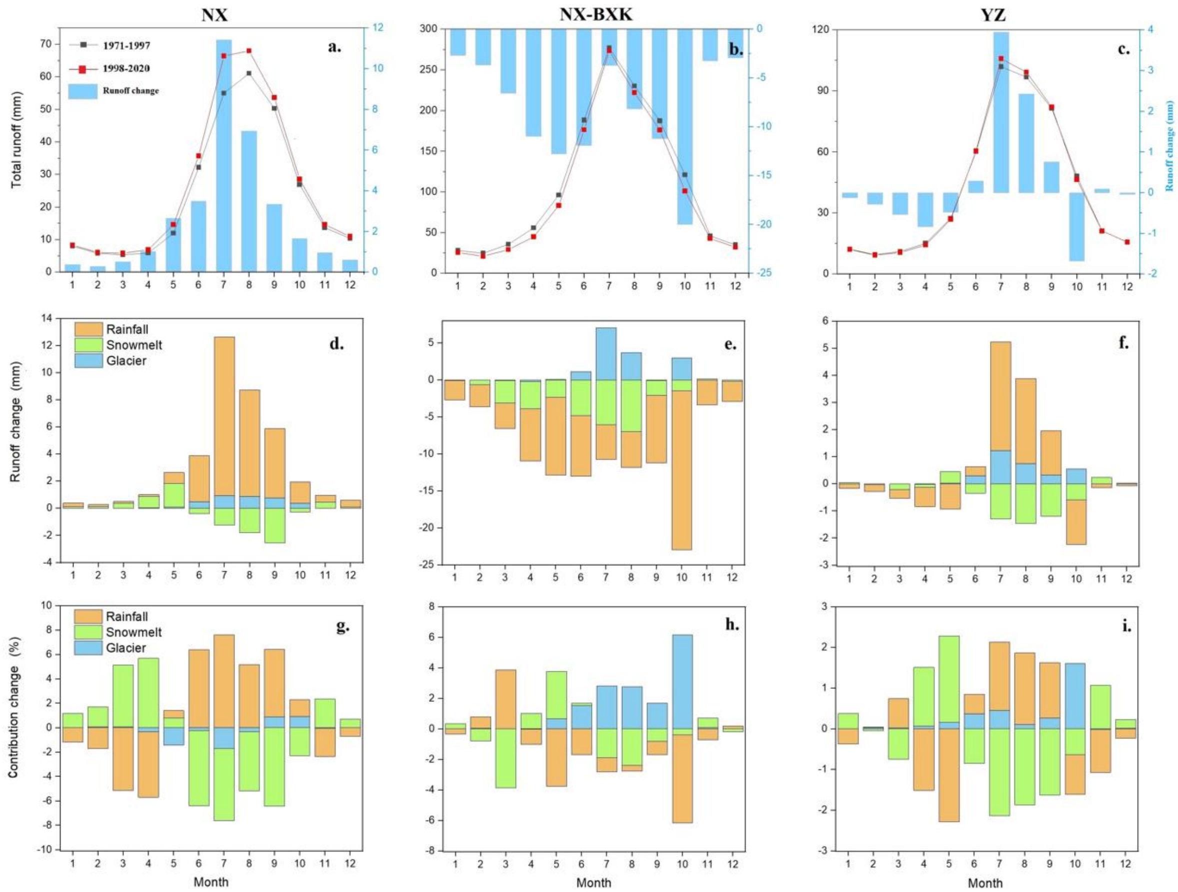

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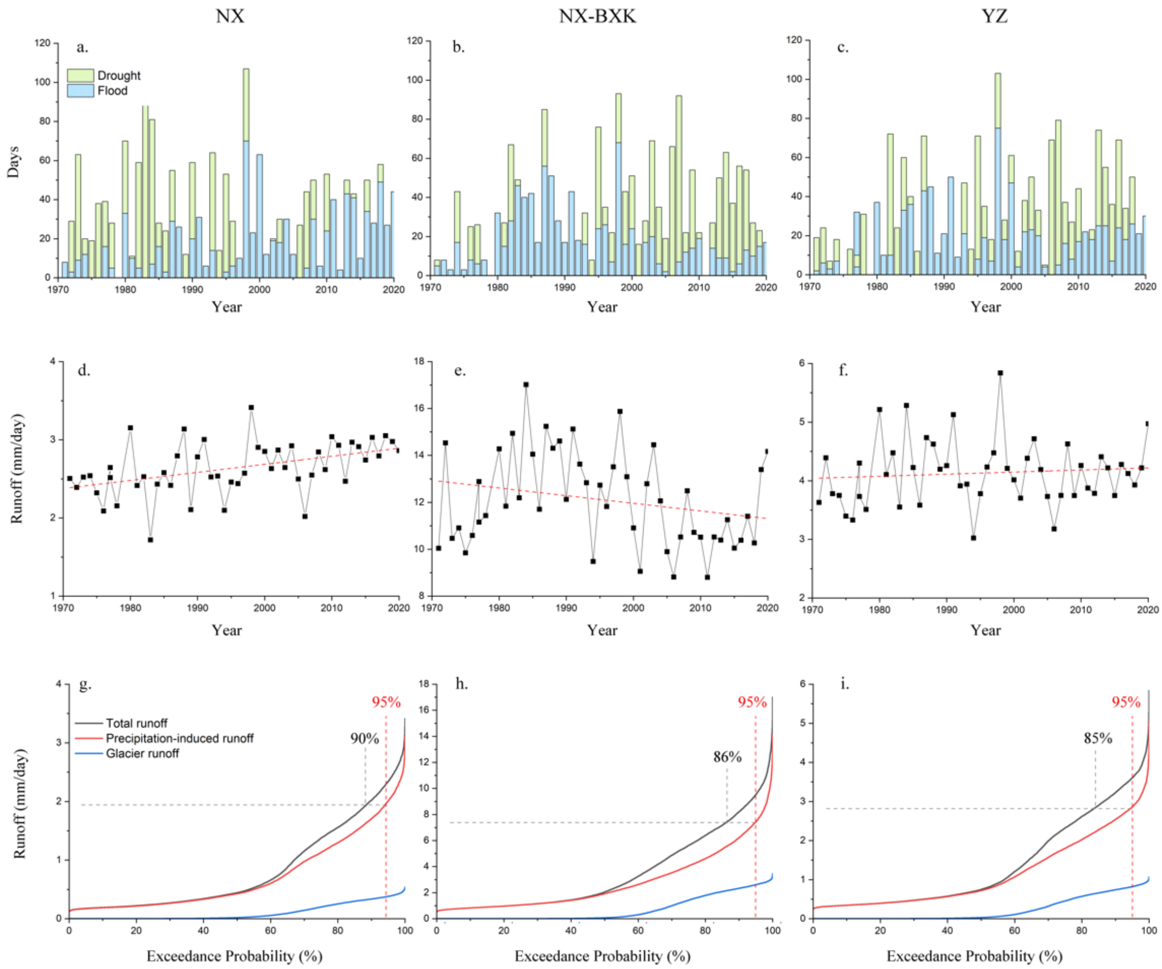

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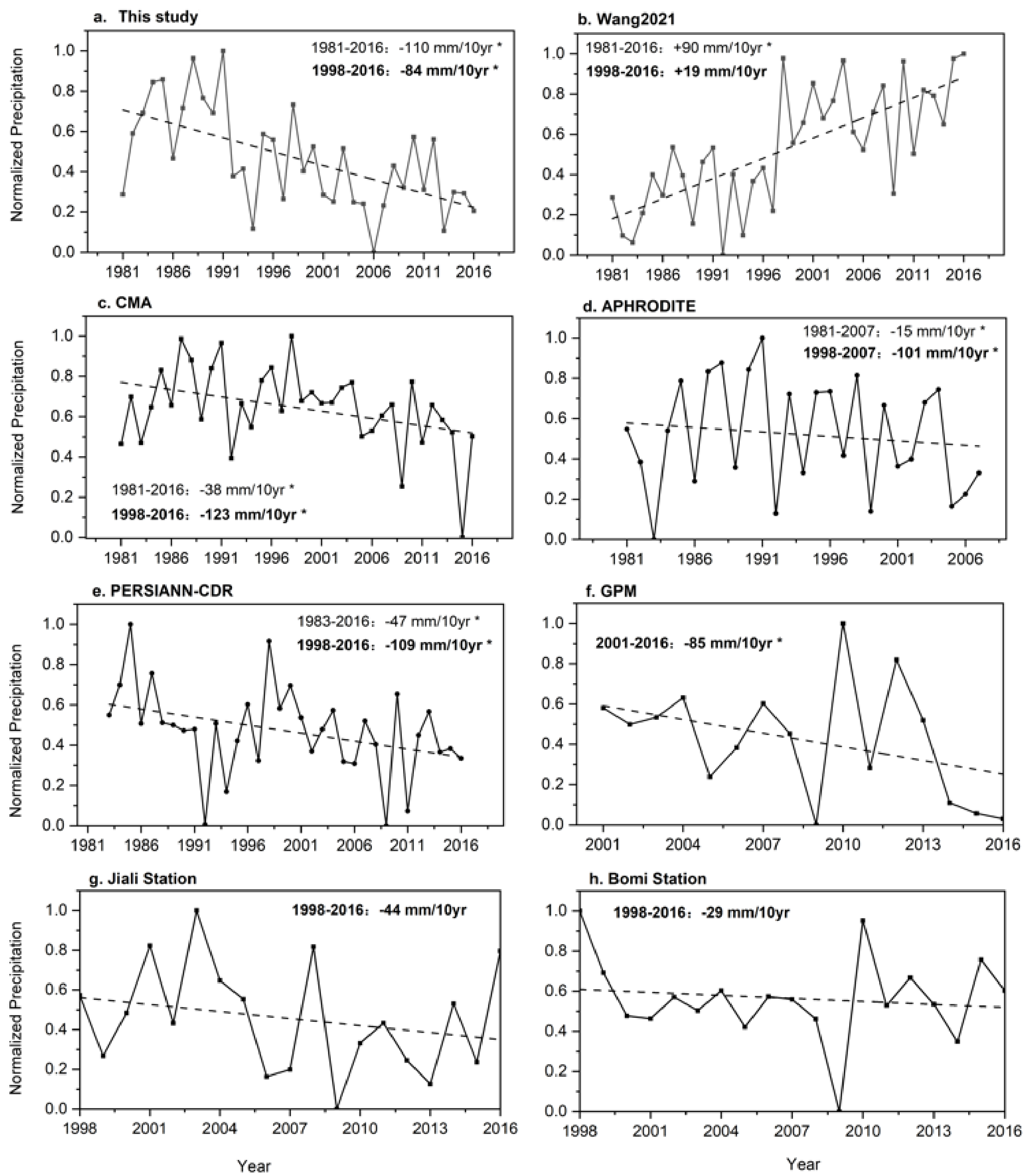

Figure 11. Time series of annual precipitation estimates from different datasets in the NX-BXK sub-basin. Asterisks indicate the 95% significance level.

Table 1. Characteristics of the six sub-basins in the Yarlung Zangbo River

		LZ	LZ-YC	RKZ	LS	YC-NX	NX-BXK	YZ
Outlet		Lhatse	Yangcun	Shigatse	Lhasa	Nuxia	Pasighat	Pasighat
Hydrological station	Name	Lhatse	Yangcun	Shigatse	Lhasa	Nuxia	Motuo	—
	Latitude (°N)	29.05	29.28	29.25	29.63	29.47	29.32	—
	Longitude (°E)	87.38	91.88	88.88	91.15	94.57	95.29	—
Drainage area (km^2)		50553	71926	11064	26235	41770	51507	253,055
Basin average elevation (m)		5370	4767	5353	5272	4937	3711	4901
Mean annual precipitation (mm) *		283	417	361	564	939	1465	774
Mean annual temperature (°C) *		-2.91	0.24	1.73	-1.28	0.97	1.21	-0.2
Glacier area (km^2)		809	640	134	257	1174	5259	8273
Glacier coverage (%) **		1.60	0.89	1.21	0.98	2.81	10.21	3.27
Degree day factor (mm °C^{-1} day^{-1})		10.97	10.97	10.97	9.2	6.8	6.5	—
Snow cover area (km^2)		7876	7344	772	6055	10129	16467	48643
Snow cover fraction (%)		15.58	10.21	6.98	23.08	24.25	31.97	19.22

*The periods of precipitation and temperature data are from 1961 to 2020.

**Glacier data are from the first China Glacier Inventory, http://westdc.westgis.ac.cn/glacier.

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Table 2. List of data used in this study for the VIC-Glacier model validation.

Data	Source	Resolution	Station name	Period
Observed runoff	Tibetan Hydrological Bureaus	Site, Monthly	Lhatse (LZ)	1971–2015
		Site, Monthly	Shigatse (RKZ)	1971–2015
		Site, Monthly	Lhasa (LS)	1971–2015
		Site, Monthly	Yangcun (YC)	1971–2015
		Site, Monthly	Nuxia (NX)	1971–2015
		Site, Monthly	Yigong (YG)	1981–2000
		Site, Monthly	Bomi (BM)	2004–2013
		Site, Annual	Motuo (MT)	2015–2019
Glacier mass balance	Institute of Tibetan Plateau Research, Chinese Academy of Sciences (http://www.tpdc.ac.cn)	Site, Annual	Gurenhekou	2005–2009
		Site, Annual	Parlung No.94	2006–2018
Glacier Inventory	The first Glacier Inventory of China (http://westdc.westgis.ac.cn/glacier)	–	–	1970s–1990s
	Randolph Glacier Inventory (RGI V6.0) (http://www.glims.org/RGI/)	–	–	2000s–2010s
Snow cover fraction	the Moderate Resolution Imaging Spectroradiometer (MODIS)10CM (https://nsidc.org/data)	0.05° × 0.05°, Monthly		2001–2019

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Table 3. Trends in precipitation, temperature, total runoff, and three runoff components and their contributions to total runoff in the YZ basins for different periods. Asterisks indicate the 95% confidence level.

Basin		NX			NX-BXK			YZ		
Period		1971–2020	1971–1997	1998–2020	1971–2020	1971–1997	1998–2020	1971–2020	1971–1997	1998–2020
Precipitation (mm/10yr)		11.7 *	2.9	-6.9	-35.0 *	52	-16.4	2.1	8.3	-8.8
Temperature (°C/10yr)		0.4 *	0.2 *	0.3 *	0.1 *	0.1	0.3 *	0.3 *	0.2 *	0.3 *
Runoff (mm/10yr)	Total	9.4 *	1.1	-3.3	-21	48.1	-0.3	3.1	8.9	-2.7
	Glacier	1.1 *	0.6	0.7	6.0 *	0.1	16.1	2.0 *	0.1	3.9
	Snowmelt	-1	0.5	-3.4	-6	20.6 *	5.7	-1.9 *	4.6 *	-1.5
	Rainfall	9.4 *	0.9	-0.6	-22	27.6	-22.1	3.0	4.9	-5.0
Contribution (%/10yr)	Glacier	-0.1	-0.2	0.3	0.8 *	-0.7	1.2	0.3	-0.4	0.8
	Snowmelt	-1.1 *	0.3	-0.8	-0.1	0.9	0.3	-0.5 *	0.6	-0.3
	Rainfall	1.1 *	-0.1	0.6	-0.7 *	-0.3	-1.6 *	0.2	-0.2	-0.5

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Table 4. Summary of relevant studies on simulated runoff component contributions in the YZ basin.

Basin	Runoff contribution (%)			Period	Method	Precipitation Data	References
	Glacier	Snowmelt	Rainfall				
Nuxia	11.6	23	65.4	1961–1999	VIC+DD	Corrected CMA data	Zhang et al. (2013)
	16	9	59	1998–2007	SPHY+DD	APHRODITE	Lutz et al. 2014
	15	27.3	57.7	1971–2000	VIC+DD	Corrected CMA data	Su et al. (2016)
	9.9	10.6	79.5	2003–2014	CREST	CGDPA, TMPA	Chen et al. (2017)
	5.5	23.1	71.4	1971–2010	VIC+DD	Interpolated CMA data	Zhao et al. (2019)
	13.9	23.8	62.3	1980–2000	VIC+DD	Reconstructed data	Sun and Su (2020)
	1.8	13.2	62.1	1985–2014	SPHY+DD	ERA5	Khanal et al. (2021)
	18.4	22	69.6	2001–2010	isoGSM	CMFD	Nan et al. (2021)
	3.5–7.2	16.6–22.3	—	1981–2019	WEB-DHM	Reconstructed data	Wang et al. (2021)
	13	***24***	***63***	***1971–2020***	***VIC+DD***	***Corrected ERA5***	***This Study***
NX-BXK	45.3	15.1	39.6	1980–2000	VIC+DD	Reconstructed data	Sun and Su (2020)
	5.7–8.2	7.2–7.8	—	1981–2019	WEB-DHM	Reconstructed data	Wang et al. (2021)
	19	***21***	***60***	***1971–2020***	***VIC+DD***	***Corrected ERA5***	***This Study***
YZ	32.7	18.4	48.9	1980–2000	VIC+DD	Reconstructed data	Sun and Su (2020)
	5.5	17.2	73.3	1981–2019	WEB-DHM	Reconstructed data	Wang et al. (2021)
	16	***22***	***62***	***1971–2020***	***VIC+DD***	***Corrected ERA5***	***This Study***

Note: VIC+DD=The Variable Infiltration Capacity (VIC) linked with a degree-day glacier melting model; SPHY+DD=The Spatial Processes in Hydrology (SPHY) linked with a degree-day glacier melting model; CREST=Coupled Routing and Excess Storage model; isoGSM=Scripps global spectral model with water isotopes incorporated; WEB-DHM= Water and energy budget-based distributed hydrological model; CMFD= China Meteorological Forcing Dataset.